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The effects of municipal waste reduction and recycling policies on the economic feasibility of landfill gas generation

Tânia Galavote [a], Gisele de Lorena Diniz Chaves [b], Luciana Harue Yamane [a], Renato Ribeiro Siman [a,*]

[a] Department of Environmental Engineering, Universidade Federal do Espírito Santo, Av. Fernando Ferrari, 514, Vitória CEP: 29075-910, ES, Brazil

[b] Department of Production and Systems Engineering, Universidade Federal de Santa Catarina, R. Engenheiro Andrei Cristian Ferreira, Trindade, Florianópolis CEP: 88040-900, SC, Brazil

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ABSTRACT

Landfill gas (LFG) projects for energy production have several advantages. However, to avoid the impossibility of these projects, it is crucial to assess the long-term effects of public policies that promote the diversion of waste disposed of in landfills. Therefore, the objective of the present work is to evaluate the effects of the application of public policies, which influence recycling, reduction of generation, and inadequate disposal reduction of municipal solid waste (MSW), in the potential of electricity generation in landfills, as well as to evaluate its effect on economic viability. A System Dynamics model was employed to estimate methane production while considering variations in the quantity and make-up of MSW over time. The results showed that the scenarios with the greatest potential for methane generation and electricity were those with less diversion of biodegradable waste. Furthermore, the economic performance demonstrated that none of the possibilities are viable except with carbon credits extra income. However, all scenarios could become viable by increasing the energy sale rate above 93.2 $USD.MWh^{-1}$. Another option calls for lowering the discount rate through government incentives to a percentage below 10 % and an investment cost below 77 % of the original value. These elements aid in long-term planning and give decision-makers a future vision of the impact of these policies.

Introduction

In developing countries in recent years, variables like population growth, economic development, and fast industrialization have contributed to a waste generation increase (Cudjoe & Han, 2020). Although the public policy implementation in these countries tries to reverse this situation, the expected results have evolved slowly in reducing the rate of waste generation and recycling (Chaves et al., 2021). In many cases, its application does not guarantee improvements in waste management (Cetrulo et al., 2018).

For instance, the Brazilian National Solid Waste Policy (BNSWP) established in 2010 (Brasil, 2010a, 2010b) includes environmental concepts typically found in developed country law (Campos, 2014; Cetrulo et al., 2018). One of them is the waste management hierarchy, which prioritizes in order of importance the waste prevention, reduction, reuse, recycling, and waste treatment, as well as the environmentally appropriate waste final disposal in landfills (Brasil, 2010b). However, even after the regulation of the law, the indicators of generation, recycling, and proper disposal progressed very slowly. For instance, per capita generation increased by 10 % between 2010 and 2019, inadequate disposal decreased by just 2.7 %, and recycling rates remained extremely low (1.2 % for recyclables and 0.4 % for composting) (SNIS, 2023).

The BNSWP's low effectiveness is related to several factors, such as

Abbreviations: AD, Anaerobic Digestion; BAU, Business as usual; BNAEE, Brazilian National Agency of Electric Energy; BNSIS, Brazilian National Sanitation Information System; BNSWP, Brazilian National Solid Waste Policy; CC, Carbon Credits; CCE, Combustion Engine Efficiency; ES, Espírito Santo; FEM, Free Energy Market; ICE, Internal combustion engines; LCOE, Levelized Cost of Electricity; LFG, Landfill gas; MCP, Methane Calorific Power; MBT, Mechanical and biological treatment units; MSW, Municipal Solid Waste; NPV, Net Present Value; PP, Payback period; REM, Regulated Energy Market; SWMP-ES, Solid Waste Management Plan.

* Corresponding author.
E-mail addresses: tania.pinto@edu.ufes.br (T. Galavote), gisele.chaves@ufsc.br (G. de Lorena Diniz Chaves), luciana.yamane@ufes.br (L.H. Yamane), renato.siman@ufes.br (R.R. Siman).

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deficiencies in penalties application for failure to comply with the law (Costa & Dias, 2020) and lack of technical training, which leads to a lack of human resources for planning, implementation, management, and supervision of legal requirements (Cetrulo et al., 2018). Approximately 50 % of Brazilian municipalities still needed waste management plans in 2017 (Costa & Dias, 2020). In addition, despite selective collection efforts in 73 % of Brazilian cities, they typically only encompass part of the urban region (SNIS, 2023). These programs still need mobilizing the populace's help for source separation and recycling (Rutkowski & Rutkowski, 2015). Other aspects concern the situation of recycling plants (Campos, 2014), such as the lack of fiscal and economic incentives for these installations and products that use recycled material (Conke, 2018). This scenario is among the causes of the continued disposal of tailings in landfills.

The BNSWP also adheres to the hierarchy of waste management and promotes waste recovery and energy use as long as it is technically feasible and environmentally beneficial (Brasil, 2010b). One of the items required in the BNSWP is the Brazilian Solid Waste Plan, which also suggests energy recovery targets in Brazilian landfills (Brasil, 2021). Currently, the country has 18 of these installations registered with the Brazilian National Agency of Electric Energy (BNAEE), with a total capacity of 175 MW (ANEEL, 2023). However, this corresponds to only 13 % of Brazilian potential, estimated at 1320 MW, which could generate around 9.3 $TWh.year^{-1}$ (Silva dos Santos et al., 2018).

The LFG energy generation is an attractive option for reducing greenhouse gas emissions and consequent inclusion in the carbon market, besides generating electricity and obtaining revenue from its sale (Cudjoe et al., 2020). However, to implement these initiatives, especially in developing nations, it is essential to determine whether they are feasible (Santos et al., 2018). Several studies approached it. For example, Barros et al. (2014) analyzed the production energy possibility in Brazil using LFG. The authors concluded that the projects are feasible in population groupings with more than 200,000 residents. Also, in Brazil, Silva et al. (2017) evaluated the feasibility of a project to serve the municipalities of the Minas Gerais state around 200,000 residents. The authors found that current conditions made the project unviable, but population growth and a discount rate lower than 15 % could make it viable. Cudjoe, Han, and Chen (2021) observed that the project is feasible in all examined locations (112 million residents) but using a higher discount rate may render it unfeasible. In China, Dai and Taghavi (2021) compared the viability between two different districts of Tehran (8.68 million residents) and Beijing (21.75 million residents). The authors concluded that the districts of Beijing have better economic performance than Tehran districts.

Other studies compared various technologies Ogunjuyigbe et al. (2017) examined the viability of incineration, anaerobic digestion, and landfill technologies in Nigeria. According to the authors, AD is more viable in the North region and landfills in the South region. In Brazil, Brito et al. (2021) mention that only the landfill was economically viable compared to AD. However, Santos et al. (2019) found that incineration and AD could become feasible if the energy price value were above 165 $USD.MWh^{-1}$. In China, Cudjoe, Brahim, and Zhu (2023) identified a price of 75.2 $USD.MWh^{-1}$ for energy generation from petroleum derived from the pyrolysis of mixed plastic waste. Also In China, Cudjoe et al. (2020) compared the viability between AD and landfills. According to the authors, both technologies are viable; although AD offers viability, they also found that a discount rate greater than 20 % could make both technologies unfeasible. The same conclusion is indicated by Obuobi et al. (2022) also in research carried out in Ghana.

However, few studies assessed scenarios of changes over time in MSW management due to the implementation of public policies. In this context, policies incentives to composting, recycling, and anaerobic digestion may interfere with the amount and composition of waste disposed of in the landfill and in energy generation (Yilmaz & Abdulvahitoğlu, 2019). Thus, it is necessary to look into the factors that influence energy production to reduce any potential dangers and improve the safety of the technology's operation (Kataray et al., 2023). Firdaus and Mori (2023), Ghimire et al. (2024), Axon and Darton (2024), for example, mention that future research should identify risks, threats, and disturbances and evaluate the reliability and resilience of clean energy systems. Therefore, it should be considered the economic and environmental aspects for more accurate and realistic modeling and thus assess threats and disturbances to the energy generation system and their long-term effects.

In this context, this current study aims to evaluate the effects of the application of public policies, which influence recyclables waste fraction recycling and organic composting, reduction of MSW generation, and reduction of inadequate disposal, in the potential of landfills energy generation, as well as to evaluate its effect on economic viability. To this end, the state of Espírito Santo, which recently developed the Solid Waste Management Plan (SWMP-ES), was the example utilized as it establishes targets for reducing the generation, recycling, and energy use of LFG (Espírito Santo, 2019). This study contributed to long-term planning since it provides decision-makers with a perspective of the impacts of policy application on LFG energy use while also contributing to long-term planning through the assessment and comparison of various uncertainty scenarios. This research is mainly relevant for policymakers in developing countries, as these countries still face many challenges and obstacles in implementing public policies. Moreover, this study contributes to the literature by providing a methodology that can assess the economic viability of LFG generation, considering changes in MSW composition over a long time.

Materials and methods

Study area

The study area is Espírito Santo (ES), a state in the Southeast region of Brazil with an estimated population (2020) of 4,064,052 inhabitants distributed in 78 municipalities and 46,074 km^2, where approximately 83 % of the population lives in urban areas (IBGE, 2022). The ES state was chosen because the SWMP-ES was instituted in 2019 to comply with the BNSWP and face the adversities related to waste management (Espírito Santo, 2019). These adversities are related to MSW illegal dumping, increases in waste generation, low recycling rates, and selective collection participation. In 2021, for example, the state dumped 32,855 tons of MSW in three irregular units (Espírito Santo, 2019). From 2009 to 2019, per-capita waste generation increased by 5 %, while organic waste's recycling rate and composting remained low, increasing only by 2 % and less than 1 %, respectively (SNIS, 2023). Moreover, although most cities in the ES state have selective collection programs, only about 28.2 % of the populace benefits from the service (Espírito Santo, 2019).

The SWMP-ES plan outlines objectives to be fulfilled through policy steps intended to, among other things, eradicate illegal dumping, increase recycling, and incentivize waste prevention (Espírito Santo, 2019). Through these policies, the plan aims to encourage the elimination of illegal disposal forms by 2024, reduce recyclable waste disposed of in landfills by 50 %, organic waste by 40 %, and reduce per capita generation by 20 % by 2040. Following the waste management hierarchy, the plan also suggests policy steps to encourage the energy generation of LFG. The suggested actions incentivize technical and economic feasibility studies for LFG energy use systems (Espírito Santo, 2019). Therefore, it is important that these studies also consider the impact assessment of possible waste diversion scenarios disposed of in landfills to avoid future interruption of energy recovery plants and unnecessary investments (Yilmaz & Abdulvahitoğlu, 2019).

Simulation model and business as usual (BAU)

The simulation model used was developed by Galavote et al. (2023) and had two parts. The model is presented in Fig. 1. The first part

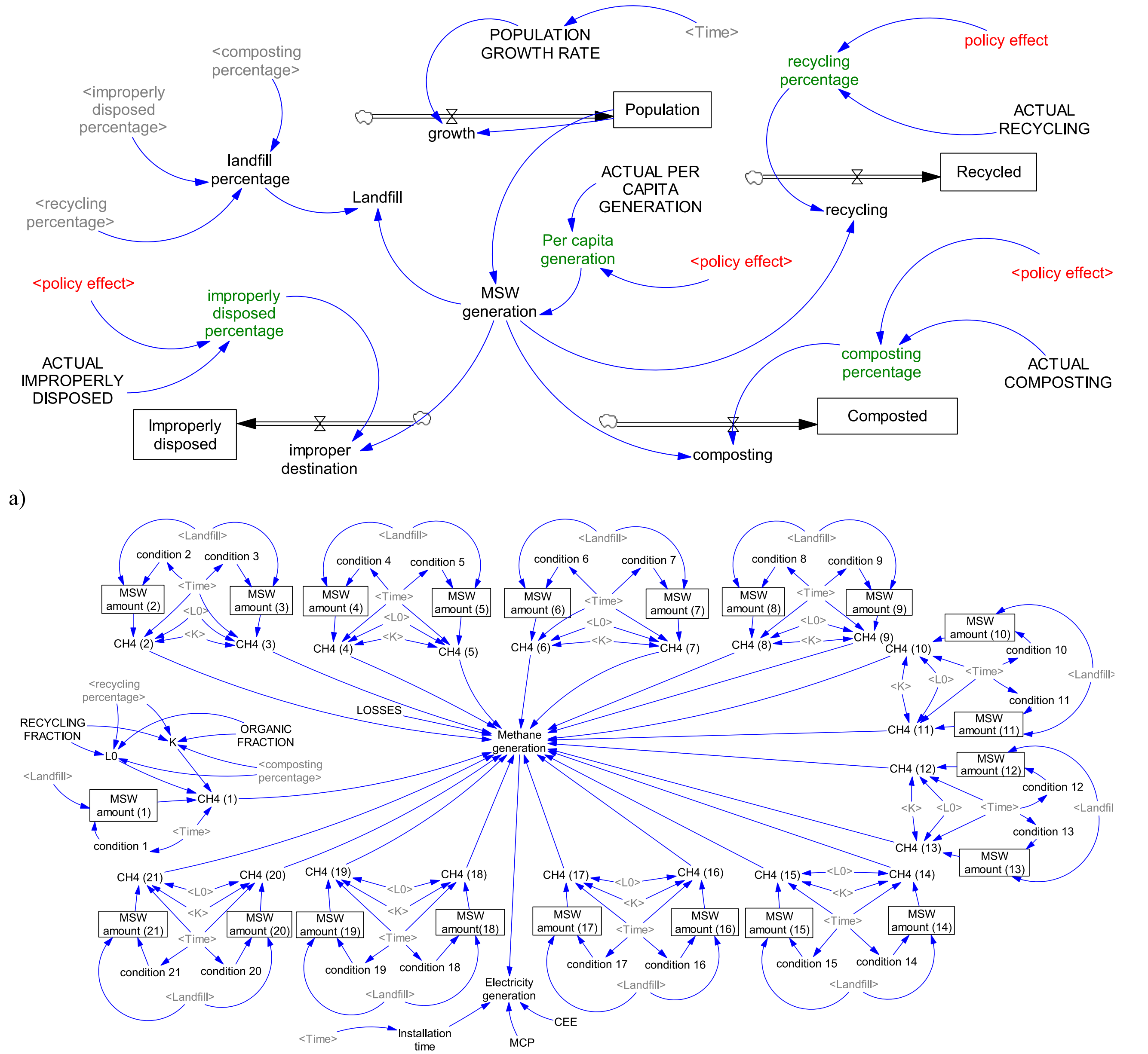


Fig. 1. a) Model (part 1) to quantify waste sent to each destination. Adapted from Galavote et al. (2023). b) Model (part 2) to estimate methane and energy generation (Galavote et al., 2023, p. 3).

(Fig. 1a) estimates waste generation (according to population and per capita MSW generation), as well as estimative the amount of waste sent for different forms of disposal and destination (composting, recycling, improper disposal, and sending to landfill). The current model has been modified from Galavote et al. (2023) in policy variables that act on other variables like recycling, composting, and improper destination percentage. In this model, Improper disposed and Per capita generation has not been considered constant variables.

In contrast, the second part of the model (Fig. 1b) estimates methane and energy generation as a function of changes in the final MSW composition for each scenario. In this paper, the model is used to evaluate uncertainty scenarios regarding the policies implementation (in red in Fig. 1a) that influence per capita generation, recycling, composting, and improper disposal (in green in Fig. 1a), and the electricity generation in a landfill. The model input equations can be found in the Supplementary Material.

The evaluation of these scenarios took place over a 20-year horizon, between 2020 and 2040, as indicated in the SPSW (Espírito Santo, 2019). For simulation, the Vensim® PLE software from Ventana Systems with a time interval of 1 and the Euler integration method was used. The BAU simulation considered current MSW management practices in the Espírito Santo state. In this way, model input data from 2020, presented in the SPSW, Brazilian Institute of Geography and Statistics Foundation (BIGSF), and the Brazilian National Sanitation Information System (BNSIS) for population, waste generation, improperly disposed, composting and recycling rate, and data from the literature for combustion engine efficiency (CEE) and methane calorific power (MCP) (Table 1). The population estimate was considered only the urban percentage, as collection coverage in rural areas is very low in ES (Espírito Santo, 2019).

Model sensitivity analysis

The sensitivity analysis examines the behavioral and model

Table 1
Business as Usual (BAU) input data for simulation.

Variable	Data	Source
Population	4,064,052 inhabitants	IBGE (2022)
Actual per capita generation	0.33 ton. Inhabitants^{-1}. year^{-1}	Espírito Santo (2019)
Actual composting index	0.1 %	SNIS (2023)
Actual MSW improperly disposed	10.5 %	SNIS (2023)
Actual recycling index	1.5 %	SNIS (2023)
Losses	35.0 %	Aghdam et al. (2018)
CEE	40.8 %	Kale and Gökçek (2020)
MCP	0.0061 MWh.[Nm^3]$^{-1}$	Santos et al. (2019)
Recycling fraction index	45.2 %	Espírito Santo (2019)
Organic fraction index	54.8 %	Espírito Santo (2019)

quantitative sensitivity to show that the behaviors of the variables under study do not change substantially when the parameters are changed within reasonable intervals (Sterman, 2000). Therefore, the parameters, Actual per capita generation, Actual composting, Actual improperly disposed, Losses, CEE, MCP, Recycling fraction and Organic fraction parameters were varied to examine their effects on waste, methane and electricity generation. Supplementary Material contains the parameters used in the sensitivity analysis.

For sensitivity analysis, it considered Actual per capita generation, Actual composting, and Actual improperly disposed of data from the 27 Brazilian states together with the Federal District obtained in SNIS, BIGSF and Brazilian Association of Waste and Environment. For the parameters, Losses, CCE, MCP, Organic fraction and Recycling fraction data identified in the literature and the database of the Generation Information System of BNSIS and the United Nations Framework Convention on Climate Change were considered. From all these data, it was possible to obtain the range of variation, mean, and standard deviation for each parameter considering Brazilian reality (Supplementary Material).

However, Actual recycling was not considered in the sensitivity analysis, because the range identified for sensitivity analysis did not include the data used in the base scenario. This occurred because the recycling data from the states of Santa Catarina (3.8 %) and Espirito Santo (1.5 %) were removed from the Brazilian average to make it fit the normal distribution; in other words, they were seen as outliers. This means that the recycling rate of these two Brazilian states are over the normal distribution of the other 25 states.

Additionally, the sensitivity test was carried out in the Vensim® PLP software using the Hipercubo Latino method, with 200 simulations. The Latin Hypercube sampling method is preferred in Monte Carlo analysis because of the efficient way it stratifies across the range of each sampled variable (Helton & Davis, 2003). In this method, for each input parameter, considering the pre-defined interval, a random and unique value is selected for the simulations (Minucci et al., 2021).

Fig. 2 presents the sensitivity analysis results for the interest variables Methane generation, Electricity generation, Landfill, Recycled, Improperly disposed, and Composted.

The color bands represent different confidence limits that vary by 50 % (yellow), 75 % (green), 95 % (blue), and 100 % (gray) for the interest variables when the input parameters are varied randomly over their values distributions. The blue line shows the base scenario results. The base scenario is found to be in the range of occurrence 50 % for the following variables: Electricity generation (Fig. 2a), Methane Generation (Fig. 2b), Landfill (Fig. 2c), Composted (Fig. 2d) and Improperly disposed (Fig. 2e). This suggests that the parameters used to obtain these variables are among the 50 % that occur most frequently, although composting almost breaks this limit. In contrast to recyclables recycling,

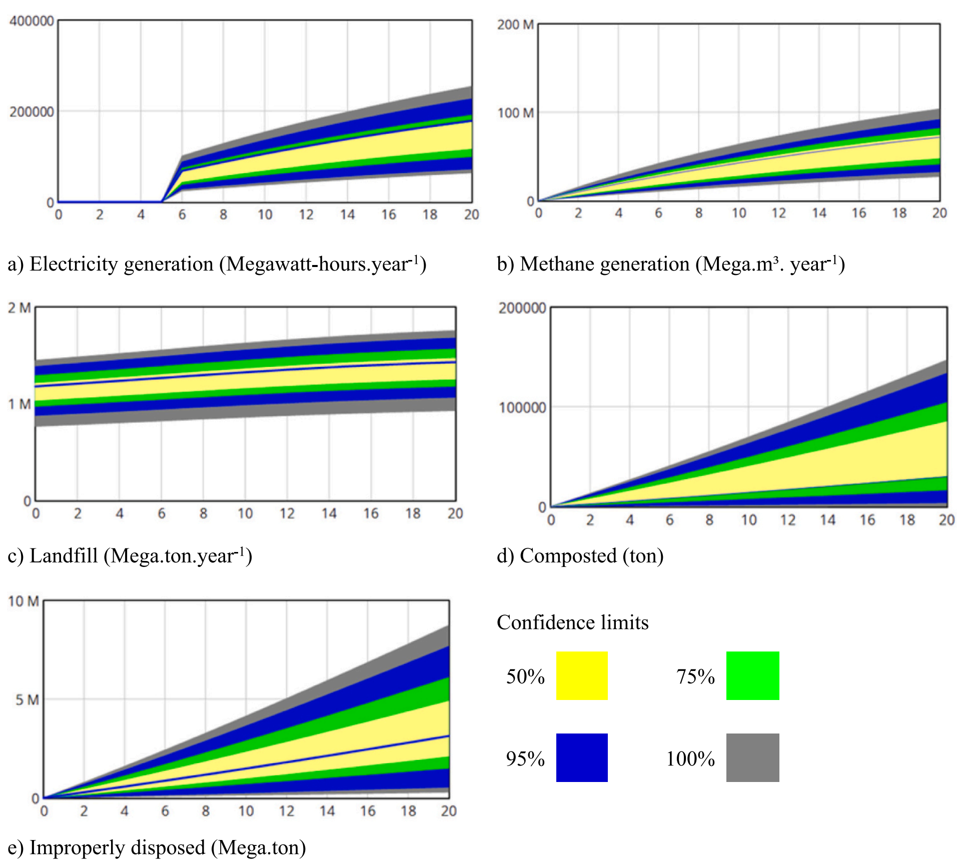


Fig. 2. Sensitivity analysis results of the interest variables over time.

the composting rates in the state of Espirito Santo are almost negligible and significantly lower than the national average, as seen in the Fig. 2d.

Furthermore, the model's behavioral sensitivity to each of these variables is not substantially changed when the input parameters are changed within the established ranges. For instance, in Landfill (Fig. 2c) the changes over time are not noticeable, different from the increasing tendency observed in Electricity generation (Fig. 2a), Methane Generation (Fig. 2b), Composted (Fig. 2d), and Improperly disposed (Fig. 2e), that suggests an increase in variability over time.

For methane generation, for instance, the 100 % confidence limits show a value range that fluctuates by the conclusion of the simulation horizon between 100 million m^3 (highest value) and 250 million m^3 annually (lowest value) (Fig. 2b). The results further reveal that electricity generation of approximately 60,000–230,000 $MWh.year^{-1}$ (Fig. 2b) may be accomplished within a 95 % confidence interval. However, electricity generation does not begin until after the fifth year due to installation time. From this, it is possible to confirm that changes in the MSW's composition, variations in the composting rates of wet waste, inadequate disposal, and waste generation rate can all have a substantial effect on methane production, and, in turn, the amount of electricity produced throughout time.

Description of evaluated scenarios

Considering the challenges to Brazil for the solid waste management policies implementation (Costa & Dias, 2020) and the challenges by the state of Espírito Santo (Siman et al., 2020) to encourage increased recycling, the reduction of inappropriate disposal and waste generation, it was simulated five planning scenarios: Audacious, Past in Brazil, Optimistic, Realistic and Pessimistic (Fig. 3).

The Audacious and Past in Brazil scenarios were based on the study by Galavote (2021). As a result, the audacious scenario assumes that the performance of the state of Espírito Santo matches that of developed nations in the reduction of MSW per capita generation, recycling, composting and MSW improper disposal. However, the scenario based on the past in Brazil implies that the state performs at the level of some Brazilian cities that have recently made a name for themselves. Each scenario (Audacious and Past in Brazil) still has three distinct behaviors, Sluggish, Intermediate and Abrupt. Such behaviors are related to the effectiveness of the public policy implementation in the variables.

In the Sluggish behavior curve, for example, the processes are not very effective initially, requiring more rigorous policies to be applied for their intensification at the end. On the other hand, in Abrupt behavior, the implementation is not resisted, which causes a considerable evolution of the variables in a very short period. In Intermediate behavior, there is some resistance at the beginning, but gradually the evolution of the axes is observed.

In the Optimistic scenario, the goals suggested by the SPSW (Espírito Santo, 2019) for inappropriate disposal elimination, recycling, and composting are fully met (100 %) up to the simulation horizon, while in the Realistic scenario, these goals are partially met (50 %). The Pessimistic scenario (BAU) is based on the current situation of no political influence. All scenarios were made from the parameters presented in Supplementary Material related to the GPC variables, percentage of recycling, composting, and inadequate disposal.

In the Optimistic and Realistic scenarios, the values are assigned gradually over the years, as suggested in the SPSW (Espírito Santo, 2019). In the Pessimistic scenario (BAU), the current values of the variables along the simulation horizon are assigned. For the Audacious and Past in Brazil Scenarios and their respective learning curves, exceptionally, the data were used to construct S-shaped curves (Table 2), as suggested by Galavote (2021). These curves represent the influence of the implementation of public policies on the investigated variables (Chaves et al., 2021). Thus, as the policy variable is qualitative and a value is assigned to it referring to its degree of implementation (x-axis) that varies from zero when no policy is applied to 1 when strict policies are applied (Ghisolfi et al., 2017).

It is also expected that the complete implementation of public policies will occur between 2020 and 2040, so a ramp function is used to represent the degree of implementation of policies over time. The function increases linearly with a defined slope between time intervals of 2020 with a 0 % implementation degree and 2040 with 100 %

Table 2
Equations for variables according to the Audacious and Past in Brazil scenarios.

Scenarios	Behaviors	Variables	
		% Reduction of MSW per capita generation	% Recycling
Audacious	Sluggish	$y = -0.100*\tanh(7x-3.050) - 0.100$	$y=0.113*\tanh(7x-3.250) + 0.113$
	Intermediate	$y = -0.110*\tanh(12x-3.890) - 0.110$	$y=0.120*\tanh(12x-4.510) + 0.120$
	Abrupt	$y = -0.236*\tanh(30x-8.576) - 0.236$	$y=0.109*\tanh(30x-9.424) + 0.110$
Past in Brazil	Sluggish	$y = -0.099*\tanh(7x-5.324) - 0.099$	$y=0.025*\tanh(7x-4.476) + 0.025$
	Intermediate	$y = -0.094*\tanh(12x-8.109) - 0.094$	$y=0.067*\tanh(12x-7.490) + 0.067$
	Abrupt	$y = -0.203*\tanh(30x-18.203) - 0.203$	$y=0.122*\tanh(30x-16.400) + 0.122$

Scenarios	Behaviors	Variables	
		% Composting	% Improperly disposed
Audacious	Sluggish	$y=0.071*\tanh(7x-3.003) + 0.071$	$y = -0.053*\tanh(7x-4.403) - 0.053$
	Intermediate	$y=0.099*\tanh(12x-4.510) + 0.099$	$y = -0.053*\tanh(12x-4.600) - 0.053$
	Abrupt	$y=0.054*\tanh(30x-8.049) + 0.054$	$y = -0.053*\tanh(30x-8.576) - 0.053$
Past in Brazil	Sluggish	$y=0.008*\tanh(7x-4.476) + 0.008$	$y = -0.053*\tanh(7x-4.860) - 0.053$
	Intermediate	$y=0.012*\tanh(12x-7.490) + 0.012$	$y = -0.053*\tanh(12x-5.300) - 0.053$
	Abrupt	$y=0.017*\tanh(30x-17.797) + 0.017$	$y = -0.053*\tanh(30x-5.307) - 0.053$

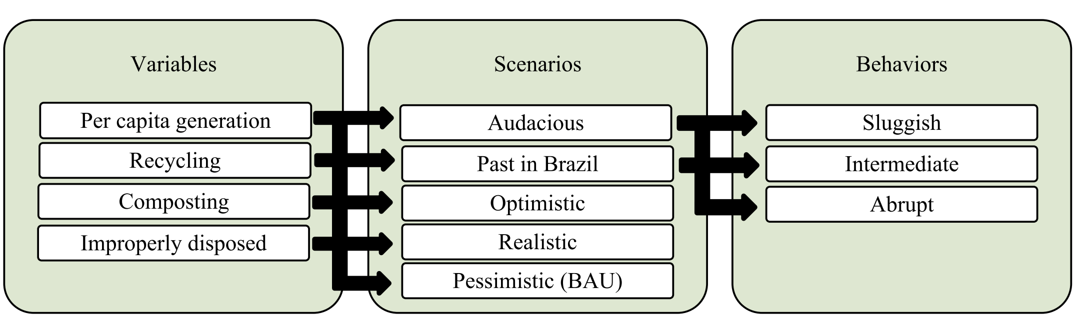


Fig. 3. Scenarios considered for simulation.

implementation of public policies (Chaves et al., 2021). The equation representing the ramp function is present in Supplementary Material, and all the equations of the variables in the model.

Economic feasibility analysis

To determine the economic feasibility, we considered the investment, maintenance, and operating costs of the thermoelectric plant powered by LFG obtained in the literature (the sources are detailed in the Table 3). Installation investment (I) was identified through Eq. 1, which relates installed power and initial investment. This equation was created using information from Brazilian thermoelectric facilities that use LFG, as Nascimento et al. (2019) provided.

$$I = 0.9388 * Power\ (MW) - 0.1658 \tag{1}$$

To calculate the investment, we considered the installed power of 1.063 MW determined by the scaling method and use of internal combustion engines (ICE) (Santos et al., 2019), as shown in Supplementary Material. Engines have an electrical efficiency of 40.8 % and lower investment, maintenance, and operating costs as a power function (USD. kW^{-1}) compared to other ICEs (Kale & Gökçek, 2020). Furthermore, a capacity factor of 0.60 was assigned, as Brito et al. (2021) and Santos et al. (2018) mentioned. The capacity factor is essential for energy utilization projects, as it indicates the relationship between the real energy generated and the installed capacity (Cudjoe, Nketiah, et al., 2021).

Maintenance and operating costs were 5 % of the initial investment in each year (Santos et al., 2018; Santos et al., 2019). An annual rate (i) of 12 % (Cudjoe, Brahim, & Zhu, 2023) was adopted and an emission factor for energy generation (F1) of 0.467 tCO2.MWh^{-1} (Otoma & Diaz, 2017). The carbon credit value adopted was 30.72 USD.tCO_2^{-1}, an average value between March 2019 and January 2021 (Investing, 2023). However, it is significant to mention that the energy recovery unit will only be able to account for carbon credits following The Intergovernmental Panel on Climate Change approval. It is a lengthy process and requires audits to be made in the enterprise (UNFCCC, 2023). It is also important to highlight that Brazil is developing its own regulation for the national carbon credits market (Brasil, 2024a). Table 3 presents a summary of the variables used to determine economic feasibility.

The economic viability analysis occurred through the Net Present Value (NPV) and the Levelized Cost of Electricity (LCOE) determination presented in Eqs. 2 and 3 (Santos et al., 2018; Santos et al., 2019). The NPV discounts all future net revenue flows to their present value (Remer & Nieto, 1995). The NPV is a viability indicator, so positive NPV values denote the project's economic viability, while negative values indicate its unfeasibility (Santos et al., 2019). The LCOE indicates the minimum tariff to be assigned to obtain viability in the project (Pratson et al., 2023). This indicator is calculated through the ratio of costs transferred to the initial year and the energy produced (Santos et al., 2019). For analysis of economic viability, the payback period (PP) of the investment was also calculated in Eq. 4, as indicated by Cudjoe, Han, and Chen (2021). The payback period is an important indicator of economic viability, as it indicates the period needed to recover the amount invested in the LFG project for energy production (Cudjoe & Han, 2020).

Table 3
Variables used for economic feasibility analysis.

Symbol	Variables	Units	Parameters	Source
E	Annual electricity production	MWh	Simulated scenarios	SD model
T	Energy sale rate	USD.MWh^{-1}	56.01	ANEEL (2020)
$C_{o\&m}$	Operation and maintenance costs	%	5	Santos et al. (2019)
i	Annual interest rate	%	12	Cudjoe, Brahim and Zhu (2023)
I	Initial investment	USD	Eq. 22	Nascimento et al. (2019)
m	The useful life of the project	year	21	Simulation time stipulated
n	Year of analysis	year	1	Intrinsic to the SD model
C	Annual Cost	USD. $year^{-1}$	Sum of $C_{o\&m}$ and Initial investment	Calculated
Rev	Revenue	USD	Annual average	Calculated
F_1	A factor of energy generation emission	tCO_2.MWh^{-1}	0.467	Otoma and Diaz (2017)
V_C	Value of carbon credit	USD. tCO_2^{-1}	30.72	Investing (2023)

$$NPV = \sum_{t=1}^{m} \frac{En.T - Co\&m}{(1+i)^t} - I \tag{2}$$

$$LCOE = \frac{\sum_{t=0}^{m} \frac{Cn}{(1+i)^t}}{\sum_{t=0}^{m} \frac{En}{(1+i)^t}} \tag{3}$$

$$PP = \frac{I + \sum_{t=0}^{m} \frac{Co\&m}{(1+i)^t}}{Rev\text{–}Co\&m} \tag{4}$$

where:

NPV: Net Present Value (Million USD);
E: Annual electricity production (MWh);
T: Energy sale rate (USD.MWh^{-1});
Co&m: Operation and maintenance costs (Million USD);
i: Annual interest rate (%);
I: Initial investment (Million USD);
n: Year of analysis (year).
LCOE: Levelized Cost of Electricity (USD.MWh^{-1});
C: Annual Cost (USD.$year^{-1}$);
t: time after the start of operation (year).
PP: payback period (year);
Rev: Revenue (Million USD);

For the energy sale rate (T), the Regulated Energy Market (REM) modality through auctions was adopted, as this proved to be more advantageous compared to the Free Energy Market (FEM) in a study carried out by Galavote et al. (2023). Therefore, it was considered that the energy would be available for the Brazilian National Interconnected Energy System, according to the price of 251.00 R$.$MWh^{-1}$ for the biogas project was established during the 23rd A5 Auction held in 2016 (ANEEL, 2020). This value was updated for 2021 (IBGE, 2023) and converted into dollars on May 30, 2021, resulting in 60.87 USD.MWh^{-1}. The potential of extra income (Eq. 5) from the selling of Carbon Credits (CC) in the Clean Development Mechanism, in addition to the sale of energy, was also taken into consideration. This revenue was calculated considering the annual carbon credit through electricity generation (CCg), referring to GHG reductions due to using LFG for electricity generation (Santos et al., 2018).

$$CCg = F_1.En.Vc \tag{5}$$

where:

CC_g: Annual carbon credit for electricity generation (USD);
F_1: Factor of energy generation emission (tCO_2.MWh^{-1});
V_c: Value of carbon credit (USD.tCO_2^{-1}).

Emissions balance

The emissions balance was carried out by evaluating the reductions resulting from LFG for energy generation. Therefore, the accumulated reductions during the 20-year simulation period in each scenario were compared with the emissions of the Brazilian electricity sector in 2023. Emissions from all electricity-generating sources and emissions produced solely using biomass (MSW, animal, wood, agro-industrial wastes, and liquid biofuels) were considered for this purpose. The Brazilian Energy Research Company data indicates that the total electricity production in 2023 was 623.6 TWh, where 8.4 % came from biomass (EPE, 2024), resulting in an emission of 90.0 kgCO2-eq.MWh^{-1} (EPE, 2020a).

Economic sensitivity analysis

The sensitivity analysis using economic indicators describes the influence of input variables on the financial balance of the enterprise (Ayodele et al., 2018; Cudjoe, Han, & Chen, 2021, Cudjoe et al., 2020). For this purpose, the operational variables' impacts (efficiency of LFG collection, capacity factor) and economic instruments (variable discount rates and investment cost) on the variables NPV, LCOE, and PP were analyzed. Table 4 presents the ranges of values assigned to the variables used in the economic sensitivity analysis.

Results

In this section, the results of the potential for methane and electricity generation are presented, as well as the financial results of the analyzed scenarios. Additionally, a sensitivity analysis of a few variables that could affect the economic equilibrium is done at the conclusion.

Methane and electricity generation potential

Over the simulation span, the potential for methane production (Fig. 4a) ranged from 5,070,300 Nm^3.year^{-1} to 95,641,500 Nm^3·year^{-1}. This range matches what Cudjoe and Han (2020) discovered in research conducted in Beijing's most populous neighborhood. Furthermore, although at the end of the simulation horizon, the worst scenario (Audacious – AB) reached only 57 % of the methane generated in the best scenario (Past in Brazil – AB), its generation is still higher than that obtained in some countries such as Gabon, Gambia, Guinea-Bissau, and Namibia. In contrast, the best scenario has the potential to be superior to countries like Congo and Sierra Leone, according to a study by Scarlat et al. (2015).

Furthermore, the amount of methane generated is greater in scenarios where there is a higher percentage of recyclable diversion and lower percentages of biodegradable diversion; this occurs due to the change in moisture and composition of the residues disposed of in the landfill (Cudjoe & Han, 2020). In other words, removing recyclables from the MSW increases the proportion of biodegradable waste, raising the landfill's moisture level and producing methane. As an example, a study carried out by Mboowa et al. (2017) on landfills in India found that areas with a high percentage of organics (92 %) and moisture content (25 % dry basis) produced 80 % more methane than other areas. This aspect appears in the Past in Brazil - AB scenario, where methane generation was considerably increased between 2030 and 2032 due to the abrupt increase in organic waste percentage (20 %) in this interval. Recognizing that a rise in methane production also causes negative impacts is crucial. Mønster et al. (2015) and Scheutz and Kjeldsen (2019) mention that despite gas collection and oxidation systems, a percentage of the methane generated will still escape into the atmosphere. Thus, as methane production in landfills rises, more methane will be released into the atmosphere, further contributing to global warming.

Table 4
Values used in the economic sensitivity analysis.

Variable	Initial value	Final value	Source
LFG collection efficiency	30 %	90 %	(Cudjoe, Han, & Chen, 2021)
Capacity factor	40 %	80 %	
Annual interest rate	5 %	50 %	(Cudjoe et al., 2020)
Initial investment (relative to the original value)	70 %	130 %	(Santos et al., 2019)

The amount of energy produced in the scenarios (Fig. 4b) was affected by methane production; as a result, scenarios with a low proportion of biodegradable waste diverted (Past in Brazil) produced more electricity. The finding in the above scenarios aligns with the findings of Cudjoe, Han, and Chen (2021) and Ayodele et al. (2017), who concluded that a high amount of organic waste in landfills contributed to the production of methane and, consequently, electricity. The situations that performed the worst scenario also had higher levels of organic waste diverted, increasing the amount of non-biodegradable recyclable waste in landfills.

This discovery aligns with the results of Cudjoe and Han (2020), who contend that the large quantity of non-biodegradable refuse, such as plastics, in landfills, slows down or prevents methane production, which also affects electricity generation. Despite this, the worst-performing scenario (Audacious-AB) reached around 1056 GWh over the simulation period. In the Past, Brazil-AB reached 1693 GWh, equivalent to 5 % and 8 % of the electricity generated from the LFG in Brazil today (ANEEL, 2023).

It is important to note that the energy generation per capita in these two scenarios is of 13 kWh.inhabitants^{-1} (Audacious-AB) and 21.0 kWh. inhabitants^{-1} (Past in Brazil-AB). For instance, the Past in the Brazil-AB scenario accordance the consortiums result of states of São Paulo and Minas Gerais. The Table 5 that presents the comparison of LFG electricity generation potential in different locations and countries.

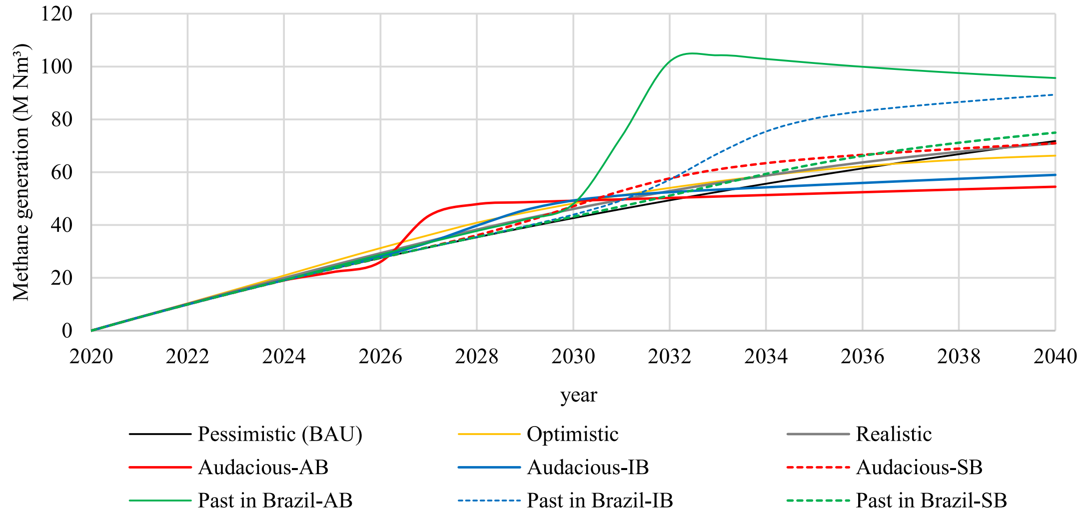
However, it is evident that these outcomes are inferior to those attained in other countries like Ghana, Nigeria, China, and Iran. Higher organic percentages waste and the waste quantity produced may be influence to this factor (Yilmaz & Abdulvahitoğlu, 2019). This aspect becomes even more noticeable when contrasted to regions in Italy, where the organic percent in MSW is substantially smaller (Caresana et al., 2011). The results also indicate a contribution of 1 % about per capita energy consumption. This outcome is consistent with findings from other sites, including the Consortia of São Paulo, Minas Gerais and Tehran cities, and Kumasi.

Economic results and emissions balance

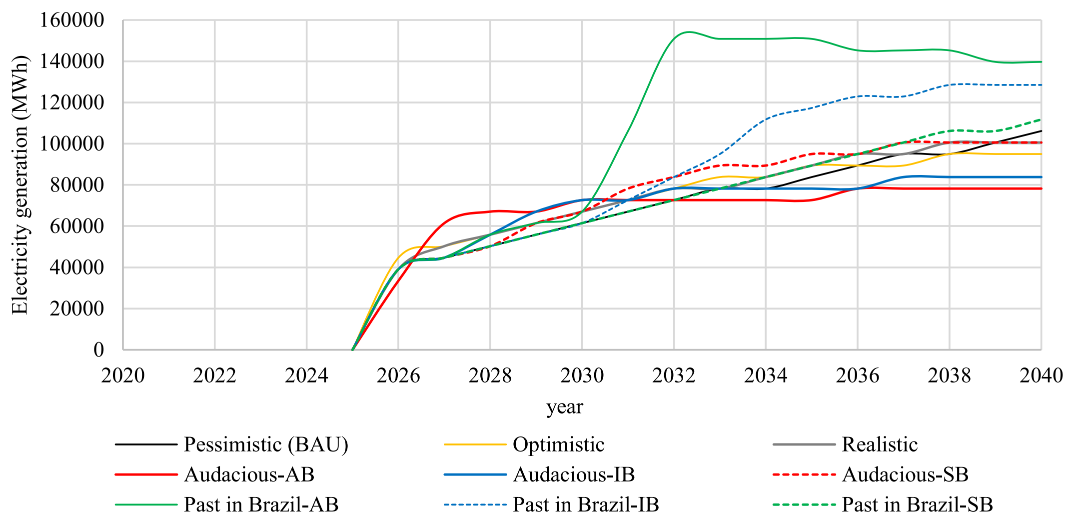
Table 6 shows the cost of the levelized energy cost as well as the financial results of the scenarios with and without carbon credit purchases. As noted, Brazilian's scenarios generated the highest revenues in the past due to their capacity to produce more energy. The Payback period would only be lower than the project horizon in three scenarios, highlighted in green.

The revenues could also be increased by 22 %, with the project included in the carbon market with a carbon credit value of 30.72 USD. tCO_2^{-1}. However, it should be noted that the CC market is subject to a great deal of volatility; for instance, between 2013 and 2018, the market faced a significant decline in values, which might cause instability in the profits of these plants (Investing, 2023). Based on this period, when the carbon credit value reached the minimum value of 3.93 USD.tCO_2^{-1} (Investing, 2023), revenues would increase only 3 %. In this case, the project would only be feasible under the Audacious-AB scenario, with an NPV of 0.42 million USD.

However, of the assessed scenarios, only Optimistic, Audacious-AB, and Audacious-IB obtained a return-on-investment period lower than the simulation period. Additional revenues from selling CC can also shorten the return-on-investment time. These were the only possibilities that produced a positive NPV (Fig. 5), demonstrating the plant's viability. This result is consistent with the research by Otoma and Diaz (2017), which found that only some of the assessed alternatives achieve profitability under the present conditions without extra carbon market revenues. Another relevant factor is the value of the LCOE, which indicates the minimum energy sales rate for the scenario to be economically viable (Santos et al., 2019). In this case, the values are above the energy sales rate used to obtain revenue, which justifies the unfeasibility



a)



b)

Fig. 4. a) Methane generation potential for the scenarios. b) Electricity generation potential in the scenarios. AB: Abrupt behavior; IB: Intermediate behavior; SB: Sluggish behavior. M Nm^3: Mega normal cubic meter.

Table 5
Comparison of LFG electricity generation potential in different locations.

Country	Regions	Population (million inhabitants)	Energy generation potential (GWh)	Energy generation per capita (kWh. inhabitants-^{1}.year)	Energy consumption per capita (kWh. inhabitants-^{1}.year)
China	Beijing-Tianjin-Hebei	112.7	12,525	111.1	31,051
	Beijing	21.8	1380	63.3	
Iran	Tehran	8.7	1540	177.0	38,133
Nigeria	Twelve metropolises*	7.0	436	62.3	2548
Ghana	Kumasi City	1.7	1686	52.4	3483
Italy	Marche Region**	1.4	5	3.9	28,910
Brazil	São Paulo consortium	34.8	978	28.1	17,300
	Mina Gerais consortium	3.5	82	23.4	

Adapted of Caresana et al. (2011), Cudjoe, Han and Chen (2021); Dai and Taghavi (2021); Ogunjuyigbe et al. (2017); Obuobi et al. (2022); de Souza Ribeiro et al. (2021), U.S. Energy Information Administration (2024).*Abeokuta, Akure, Onitsha, Abakaliki, Benim, Port, Harcourt, Abuja, Ilorin, Bauchi, Jalingo, Dutse, Katsina; ** Ancona, Ascoli Piceno, Macerata, Pesaro e Urbino e Fermo.

Table 6
Economic results for each evaluated scenario.

Scenarios	Behaviors	No carbon credits sale		With carbon credits sale		LCOE (USD.MWh^{-1})
		Revenue (Million USD)	PP (years)	Revenue (Million USD)	PP (years)	
Pessimistic (BAU)		71.5	27.7	87.0	22.7	89.4
Realistic		73.7	23.3	89.6	19.4	75.3
Optimistic		74.7	24.7	90.9	20.5	79.9
Audacious	Abrupt	67.6	20.2	82.2	17.0	64.5
	Intermediate	69.0	21.6	84.0	18.1	69.6
	Sluggish	76.5	24.3	93.1	20.2	78.8
Past in Brazil	Abrupt	108.3	27.2	131.9	22.4	88.0
	Intermediate	87.2	29.0	106.2	23.7	93.2
	Sluggish	74.4	28.5	90.5	23.3	91.7

LCOE: Levelized Cost of Electricity; PP: Payback period.

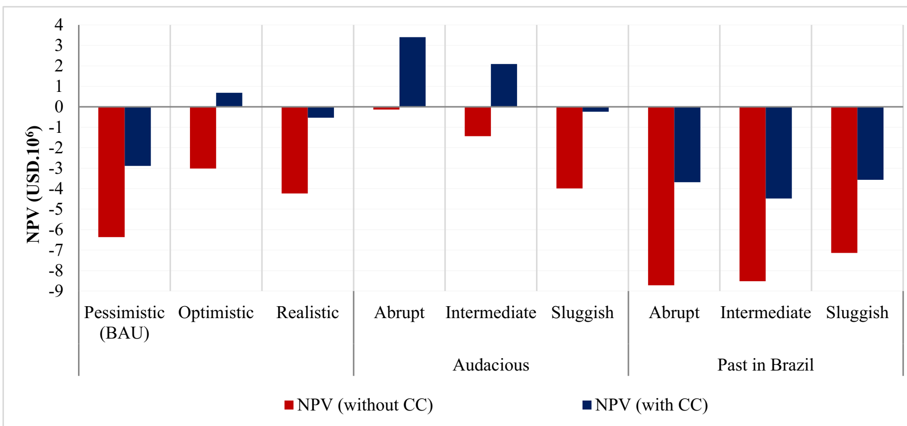


Fig. 5. NPV with and without the sale of carbon credits for the scenarios. AB: Abrupt behavior; IB: Intermediate behavior; SB: Sluggish behavior; NPV (without CC): Present Net Value without carbon credit sale; NPV (with CC): Present Net Value with carbon credit sale.

of the evaluated scenarios.

The Supplementary Material presents the comparable emissions for each scenario over the simulated period. The decreases exceed 490,000 tCO_{2eq} in the worst scenario (Audacious-AB), surpassing 790,000 tCO_{2eq} in the greatest scenario (Past in Brazil-AB). Furthermore, a comparison was made between the avoided emissions and energy production from alternative sources. Compared to the entire Brazilian electricity matrix, for example, the scenarios could mitigate only 0.9 to 1.4 % of CO_{2eq} emissions; however, comparing only the electricity matrix from biomass, this potential reaches a significant 10.4 to 16.7 %, depending on the scenario.

Sensitivity analysis and suggestions for economic rebalancing

Sensitivity analysis determined how initial investment, capacity factor, interest rate, and LFG collection efficiency variations would affect NPV, LCOE, and PP. At first, the impact of the variation of each parameter was verified separately, keeping the other parameters constant. Therefore, reductions in the initial investment increase the project viability (NPV) and reduce the LCOE values and the payback time, as observed in the study by Santos et al. (2019). However, for all scenarios, the NPV only became positive when the initial investment was less than 68 % of the investment adopted, a percentage outside the initial range. Furthermore, reductions in the interest rate increase the NPV and reduce the LCOE and the payback period, as indicated by Cudjoe, Han and Chen (2021). In this case, discount rates of less than 8 % made all scenarios viable.

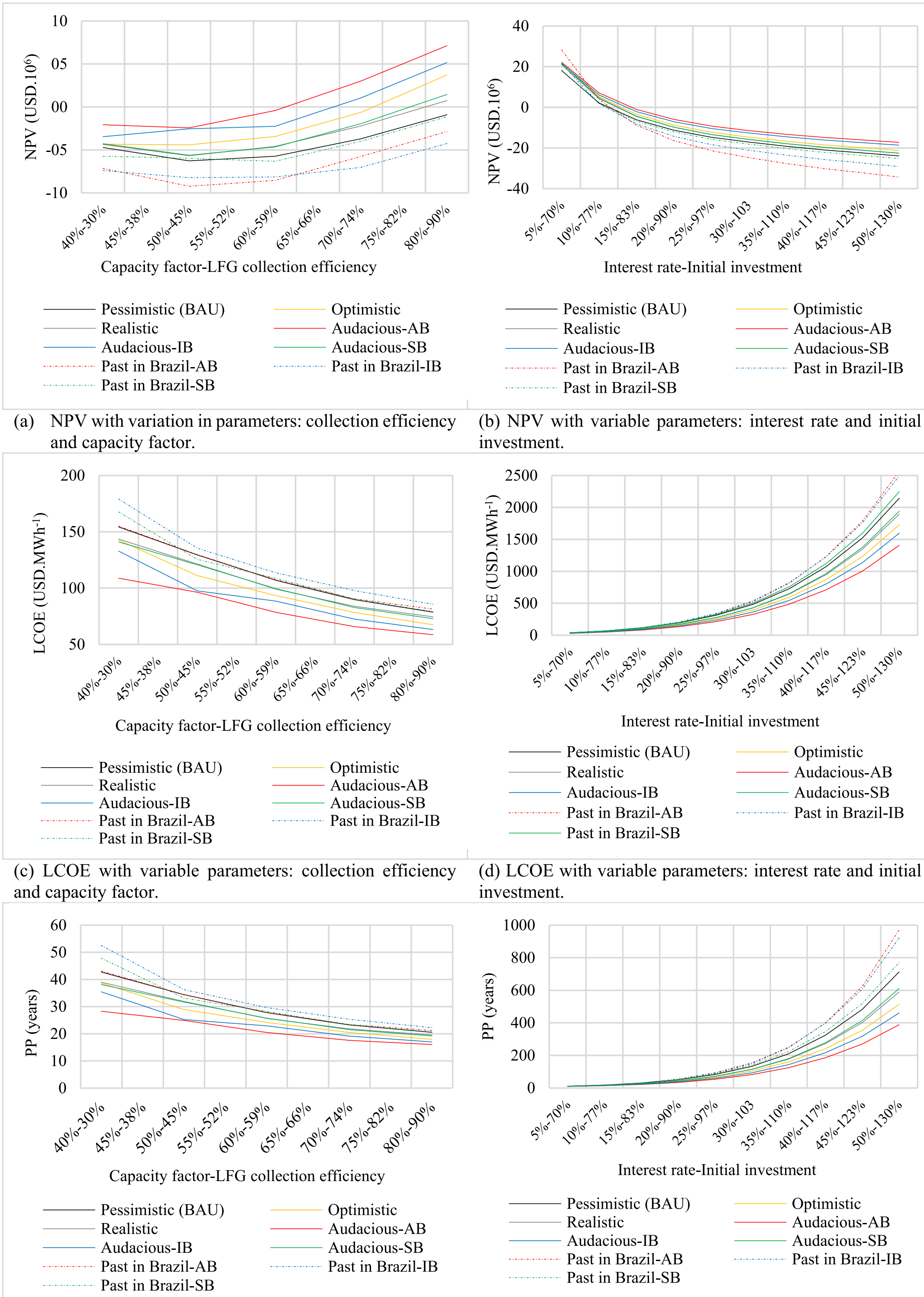
Additionally, raising the capacity factor shortens the payback time, lowers LCOE values, and increases project viability, as discovered by Ayodele et al. (2018). A capacity factor greater than 88 %, outside the stipulated initial range, turns all scenarios viable. Furthermore, the increase in LFG collection efficiency collaborates with the increase in NPV, reductions in LCOE values, and payback period (Cudjoe, Han and Chen, 2021). However, neither scenario became viable. This lack of viability is likely related to using the installed power to calculate the initial investment. This calculation is proportional to the available power and the LFG collection efficiency.

Subsequently, due to the individual sensitivity analysis results for the evaluated parameters, a sensitivity analysis grouping operational was conducted (capacity factor and LFG collection efficiency) and economic (interest rate and initial investment) parameters. As seen in Fig. 6(a), (c), and (e), the increase in the LFG collection efficiency, which in turn also influences the increase in the capacity factor, tends to rise the NPV and reduce the LCOE and the period return. However, only Optimistic, Realistic, Audacious-AB, Audacious-IB, and Audacious-SB scenarios become viable. Such values are better detailed in Supplementary Material. On the other hand, discount rates below 10 % combined with an initial investment below 77 % of the initial value make all scenarios viable and considerably reduce the LCOE values and payback period, as seen in Fig. 6(b), (d) and (f).

Discussion and political implications

Recycling and composting lower the refuse quantity dumped in landfills and extend its usable life (Xiao et al., 2020), which is advantageous in areas with limited or expensive land (Santos et al., 2019). Moreover, it lessens methane emissions, a greenhouse gas 21 times greater than CO_2 (EPA, 2017). An estimated 16 % of Brazil's methane emissions are attributed to the waste sector, with landfills accounting for most of these emissions (Embrapa, 2024).

The diversion of recyclables also makes it possible to increase revenues in WPO since one of the main challenges of these organizations is to



(a) NPV with variation in parameters: collection efficiency and capacity factor.

(b) NPV with variable parameters: interest rate and initial investment.

(c) LCOE with variable parameters: collection efficiency and capacity factor.

(d) LCOE with variable parameters: interest rate and initial investment.

(e) PP with variable parameters: collection efficiency and capacity factor.

(f) PP with variable parameters: interest rate and initial investment.

Fig. 6. Result of sensitivity analysis for NPV, LCOE and PP. NPV: Net Present Value; LCOE: Levelized Cost of Electricity; PP: payback period.

increase access to this waste (Dutra et al., 2018). On the other hand, organic waste diverted to composting and mechanical and biological treatment units (MBT) generates revenues through the sale of compost, biofertilizers, methane, or energy in the case of MBTs (Li et al., 2017). According to research by Cudjoe, Nketiah, and Zhu (2023), for instance, the annual energy produced by biomethane obtained from food waste may make up 3.4 % of the anticipated electricity needs of African countries.

However, the diversion of organic waste impacts the generation and subsequent LFG use. For example, there was a higher percentage of biodegradable deviations in the worst-performing scenarios. This finding is consistent with those of Altan (2015), whose authors hypothesized that Turkey's environmental policies, which promote the transfer of biodegradable waste, could decrease LFG production by 40 %

by 2040. On the other hand, the recyclables diversion (as in the scenarios based on the Past BR) is a fair practice for generating LFG since the percentage of biodegradable waste in the landfill tends to increase due to the recyclable diversion.

In this context, the production of electricity also increases. For example, the electricity generated over the simulation period in the Audacious-AB scenario could serve 392,699 inhabitants in one year, while the scenario based on the Past BR-AB would serve 629,565 inhabitants. This calculation bases its analysis on residential consumption in the Southeast (including Espírito Santo) during 2019, which comprised 2698 $kWh.hab^{-1}$ (EPE, 2020b). Electricity generation in these two scenarios would serve approximately 9.7 % (Audacious – AB) and 15.5 % (Past in Brazil - AB) of the state's population in one year.

This result is relevant because represents around 50 % (Audacious-AB) and 80 % (Past BR-AB) of the electrical matrix of the state of Espírito Santo in 2022 (ARSP, 2023). In addition, the need to diversify Brazil's electricity matrix, highly dependent on hydroelectric plants, makes scenarios significant for serving the state's population. This dependency causes periods of scarcity of rain, that are turning more frequent, leading to an increase in the energy tariff. This dependency and even cause blackouts in the electricity sector, as was seen between 2001 and 2002 (Lara Filho et al., 2019), as is also the case in South Asia (Rasheed et al., 2020).

Past in Brazil scenarios have a material recycling rate much higher than the composting rate (Supplementary Material). In the Past in Brazil - AB scenario, for example, up to the simulation horizon, around 24 % of dry waste and only 3 % of organic waste are diverted from landfill to recycling. This significantly raises the generation of LFG. Although the scenario Past in Brazil produces more LFG and electricity, they are less viable compared to the additional scenarios. The high installation cost of Past in Brazil is likely the reason for its lower viability compared to other scenarios. This cost is calculated based on the installed power directly related to the higher available power in these scenarios. Therefore, the greater the installed power, the greater the investment costs, which directly influences the project viability.

On the other hand, even if unfeasible at first, the Audacious scenario has the highest NPVs. It is similar to the values of Santos et al. (2019) and Brito et al. (2021) for Brazil, around 0.6 $USD.10^6$ and 0.2 $USD.10^6$, respectively. The authors also compared different technologies and concluded that obtaining electricity from LFG is more feasible, unlike what was mentioned by Cudjoe et al. (2020) and Ogunjuyigbe et al. (2017), who point to anaerobic digestion as the most viable in China and Nigeria, respectively. Brito et al. (2021) mention that in Brazil, the biogas generation in AD is insufficient to compensate for installation, maintenance, and operation costs over the years. Moreover, the alternative would be economically attractive if used for heating and not for electricity generation.

However, if the estimated value of LCOE exceeds 111.2 $USD.MWh^{-1}$, all scenarios are feasible (have positive NPV). In this case, it would be interesting to hold specific auctions for electricity generation projects from LFG (Santos et al., 2019). In 2021, BNAEE held an exclusive auction for electricity generation projects from MSW, only for thermal processes such as incineration and gasification (ABREN, 2021). Since it becomes challenging to participate in public auctions with other less costly renewable sources, this effort is crucial to making this project feasible.

The income growth from the carbon credits selling is another factor that may influence positively the NPV (Santos et al., 2019). These credits are certificates issued for projects that manage to reduce or remove greenhouse gas emissions. These projects include, among others, forests, initiatives to reduce deforestation, and generators of renewable energy such as electricity from LFG (UNFCCC, 2023). After validation and verification of the project, carbon credits can be registered in international organizations like the United Nations (UNFCCC, 2023) or registration systems like the Brazilian Public Emissions Registry (Brazil, 2024). From this, project administrators can receive additional revenue from carbon credits. As agreed in the Kyoto Protocol, these revenues come from developed nations that purchase these credits to meet their country's emission reduction targets (Purmessur & Surroop, 2019).

In Brazil, a bill is currently Senado Federal being processed that creates the Brazilian Greenhouse Gas Emissions Trading System. The political instrument will establish emissions ceilings and guidelines for the carbon credit sales market. The bill sets a limit on greenhouse gas emissions for companies. Those who do not meet the target will be able to offset their emissions by purchasing carbon credits, and companies are allowed to sell the difference on the market if they issue below the cap (Brasil, 2024b). Furthermore, Technical Guidance to address the basic requirements for recognition, measurement, and disclosure of decarbonization credits, which must be observed by entities in the origination, negotiation, and acquisition to meet decarbonization targets will be approved soon in the country (Brasil, 2024c).

In addition, other types of economic incentives may be relevant factors to achieving the viability of this type of technology. Sensitivity analysis, for instance, showed that economic factors are more successful than operational variables in attaining viability. Therefore, reduced investment costs below 77 % of the initial cost and discount rates below 10 % make all scenarios viable. Government benefits, like tax breaks, subsidies, and finance credits, could lower investment costs (Baena-Moreno et al., 2020; Shirmohammadi et al., 2020).

Tax relief is provided to help investors mitigate investment risks through tax reduction/exemption of machinery, equipment, raw materials, imports, and even income tax exemption for legal entities (Laohalidanond & Kerdsuwan, 2021). For instance, Jordan has increased its use of renewable energy sources in recent years thanks to policies encouraging their growth, such as a 100 % tax break for new projects. As a result, the country's portion of renewable energy sources in its overall energy supply has increased to 7 % (Abu-Rumman et al., 2020).

On the other hand, investment subsidies are granted by the government as a percentage of the initial investment costs and are an option to finance projects in which the initial investment is greater than the operational costs (Theuerl et al., 2019), such as waste energy recovery projects. Baena-Moreno et al. (2020) mention that subsidies applied to reduce 10 % of the initial investment would be sufficient to ensure the viability of biomethane utilization projects in Spain. In the European Union, granting subsidies to AD plants stimulated a 17 % growth in biomethane generation between 2005 and 2015 (Bahrs & Angenendt, 2019). In the Netherlands, a study by Achinas et al. (2019) compared the feasibility of AD projects with and without incentives through subsidies. According to the authors, subsidies increased NPV values and made the project more profitable.

In Brazil, the Emergency Wind Energy Program was created in response to the energy crisis of 2001 that resulted in electricity rationing (Werner & Lazaro, 2023). Its goal was to subsidize the wind energy market and produce 1050 MW from this source (Werner & Lazaro, 2023). This program contributed to wind energy accounts for 12 % of the electrical matrix currently (EPE, 2024). However, Axon and Darton (2024) mention that subsidies need to be concentrated in applications that would be difficult to decarbonize in other ways, such as those derived from biomass to replace fossil fuels.

Finally, there are several ways to raise funds for this kind of initiatives. Equity capital, for example, comes from the business owners, which makes the modality safer since interest is not charged (Sebrae, 2015). As the discount rate is calculated based on the equity cost and the cost of debt needed to implement the project, this rate modality assumes a minimum value of around 4 %, as there is no borrowed capital (Ramos et al., 2020).

The credit modalities can occur through financing (short term) and loans (long term). This capital usually comes from financial institutions (Sebrae, 2015), and the interest rates arising from this capital vary by credit modality, financial institution, person, or entity (BACEN, 2019). In Brazil, financial institutions such as the Brazilian National Bank for Economic and Social Development are sources of funds for energy generation projects from MSW through programs such as the Climate Fund and Energy Generation Auctions (Espírito Santo, 2019). In addition to ensuring the project's viability, Axon and Darton (2024) note that funding availability is critical to lowering the risks involved in turning biomass into strictly specified products that have the potential to displace fossil fuels.

Table 7 presents suggestions to make the scenarios viable, such as an increase in the value of the energy sale rate and reductions in the discount rate through investment with equity and taking credit through government programs.

In addition to the economic incentives mentioned for encouraging the LFG energy generation, aspects linked to MSW management must also be considered as they can impact in technology implementation. For instance, ineffectively enforcing penalties for legal violations can jeopardize recycling and encourage illegal MSW disposal, diverting waste from landfills and causing negative impacts on the environment. This scenario is very common in Brazilian small municipalities. These municipalities generally have waste managers without adequate technical training, leading to a shortage of human resources to plan, implement, manage, and supervise legal requirements. Another aspect is the landfill fees that could be an alternative to turn landfills more costly and consequently divert waste from it. Panzone et al. (2021), for example, mention that a 1 % increase in the landfill rate reduced waste sent to landfill in England by 1.3 %. However, the implementation of this economic instrument requires effective control and supervision to also avoid an increase in inappropriate disposal (Seacat & Boileau, 2018).

Conclusion

Through scenarios, the present study assessed the impact of policies that affect recycling, reduction of MSW generation, and improper disposal on the potential to generate electricity from LFG and its economic feasibility. It found that the scenarios with the highest potential for generating methane and electricity were those with less diversion of biodegradable waste. In addition, the financial results showed that only the scenarios are viable when considering additional revenues from the sale of carbon credits, mainly in scenarios with high rates of organic waste diversion and consequently lower installed powers.

However, one of the alternatives to make all scenarios viable is to increase the energy sales rate above 111.2 USD.MWh^{-1}. In this case, one possibility would be exclusive auctions for projects using LFG for electricity generation, which could make them more competitive without less expensive renewable sources. Another option is to decrease the discount rate to less than 10 % while maintaining an investment cost of less than 77 % of the original worth. Government benefits are required for this to occur, such as tax breaks on machinery, equipment, raw materials, and imports, as well as subsidies on the cost of the original expenditure. These factors would be crucial to advancing green energy options and helping to diversify Brazil's power grid, which is presently largely reliant on hydroelectric plants.

Table 7
Economic rebalancing suggestions for scenarios (NPV: Million USD).

Scenarios		*Rate = 111,41 USD. MWh^{-1}	** Annual interest rate: 4 %	*** Annual interest rate: 8 %
Pessimistic (BAU)		5.52	14.19	1.03
Realistic		9.61	18.80	4.91
Optimistic		8.37	17.73	3.71
Audacious	Abrupt	11.96	20.22	7.34
	Intermediate	10.59	19.24	6.11
	Sluggish	8.79	18.67	4.20
Past in Brazil	Abrupt	8.49	23.24	2.73
	Intermediate	5.30	16.75	0.48
	Sluggish	5.07	14.20	0.52

NPV: Net Present Value (Million USD). Source: *Energy utility fee in ES (EDP, 2021); ** Annual interest rate with equity capital (de Souza Ribeiro et al., 2021; Ramos et al., 2020); *** Annual interest rate with credit taking, Climate Change Adaptation Program (Moraes & Abreu, 2020).

This study indicates that government incentives are necessary to promote renewable alternatives such as LFG energy use. However, a large portion of Brazil's government incentives are focused on alternative renewable energy sources, such as wind, solar, and hydroelectric power. This factor could impede the advancement of biomass-based energy sources. Therefore, as landfills are the primary option for disposing of MSW in an environmentally appropriate manner in the country, decision-makers should focus their efforts on encouraging LFG energy. Encouragement of this alternative can also aid in the decrease and eventual elimination of improper MSW disposal, which is still a problem in some parts of Brazil, particularly in the less developed northeast and north of the country. In addition, reduces the disposal costs as well; this is an issue that mostly affects developing countries with limited resources for MSW management.

Apart from the absence of governmental incentives, novel renewable energy sources like biomass may face risks due to alterations in political and regulatory strategies linked to the political goal of successive administrations. Given this, future studies should carefully evaluate the risks and obstacles related to producing energy from biomass in Brazil as well as the business model for LFG's energy generation in the Brazilian distribution market. Evaluate the social and environmental impacts of energy use from LFG considering changes in the composition of MSW triggered by policies to promote material recycling and composting. We also suggest that future studies investigate potential impacts on the geotechnical structure of the landfill of greater humidity brought on by the diverting of recyclables. In addition, using a longer horizon for the simulation is suggested, specifically after the year of landfill closure. This aspect will more accurately determine the ideal installed power and the required initial investment (referring to the longer horizon simulation).

This study also contributed to long-term planning, providing decision-makers with a broad view of the effect of implementing public policies that encourage recycling and reduction in the per capita generation of MSW and, simultaneously, the energy use of LFG. This aspect is highly relevant for policymakers in developing countries, as these countries still face many challenges and obstacles in implementing public policies.

These study results adhere to the principles of NPSW (Brasil, 2010a, 2010b), mainly in the instrument related to solid waste management hierarchy that indicates in priority order the prevention, reduction, reuse, recycling, energy generation, treatment, and adequate disposal of solid waste. Furthermore, this study complies with the NPSW in terms that the energy use of waste is encouraged if it is technically feasible and environmentally beneficial. The results for reducing GHG emissions also can help Brazil achieve the objectives set out in the United Nations Climate Change Conference (COP28). GHG emissions can be reduced by up to 79.0246 tCO2 in the best scenario using LFG for energy generation.

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CRediT authorship contribution statement

Tânia Galavote: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gisele de Lorena Diniz Chaves:** Writing – review & editing, Supervision, Software, Conceptualization. **Luciana Harue Yamane:** Writing – review & editing, Supervision. **Renato Ribeiro Siman:** Writing – review & editing, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2024.101493.

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